

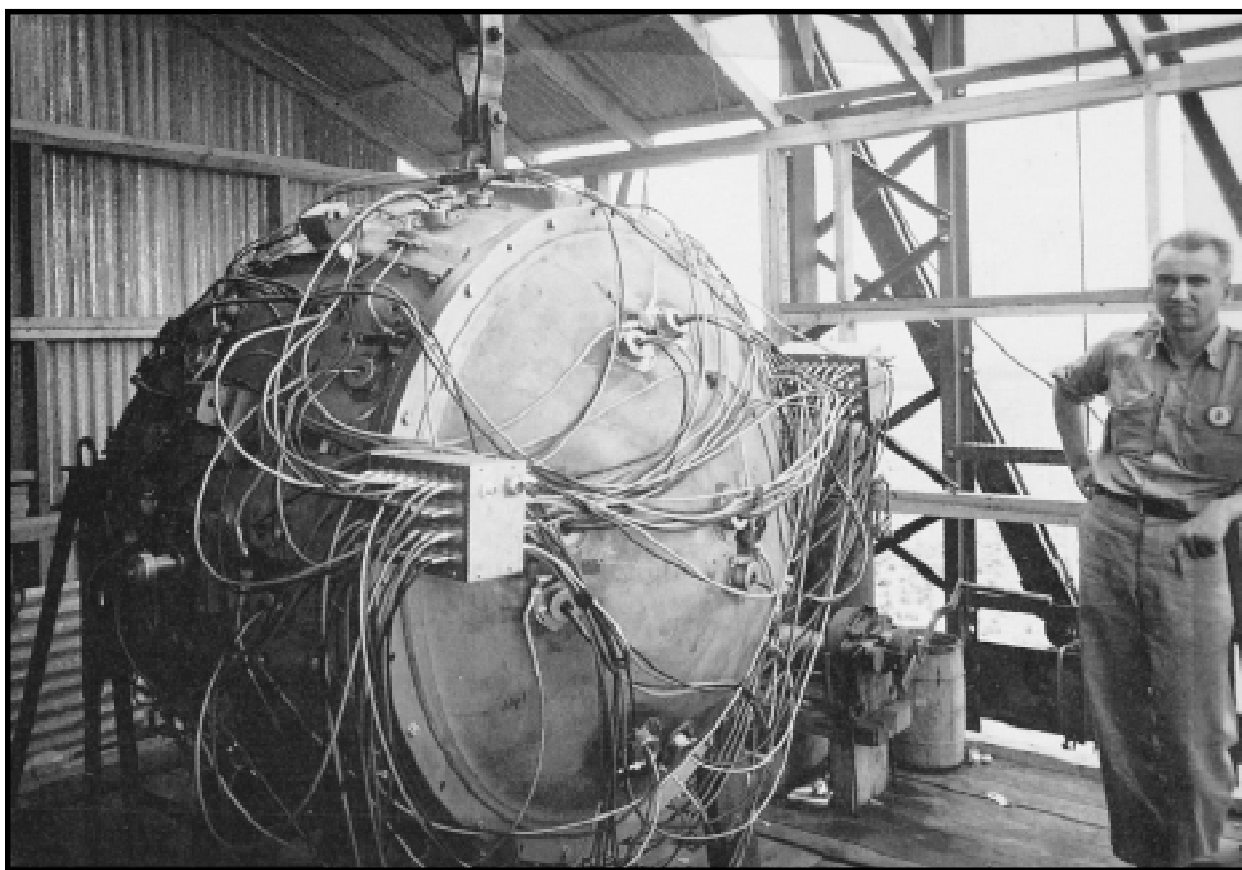
2. NUCLEAR WEAPONS PRODUCTION PROCESSES AND HISTORY



Hanford N Reactor opening ceremony. President John F. Kennedy spoke at the opening ceremony for the Hanford N Reactor, which was designed to produce steam for electricity generation in addition to plutonium for the nuclear weapons stockpile. It was Hanford's ninth and last production reactor. The N Reactor was shut down permanently in 1986. 100-N Area, Hanford Site, Washington. September 1963.

OVERVIEW

It is necessary to understand the operation and history of the nuclear weapons complex to properly attribute the resulting waste, contaminated media, surplus facilities, and materials in inventory. Understanding the processes begins with understanding nuclear weapons themselves and the activities that went into making their materials and components. This chapter briefly describes nuclear weapons, their production processes, facility locations, and the history of events that generated today's legacy. Appendix B provides more detailed history and more technical descriptions of key nuclear weapons production processes.



The "Gadget." Dr. Norris E. Bradbury stands next to the world's first nuclear explosive device, code-named the "Gadget," which yielded the equivalent of 21,000 tons of TNT when it detonated at 5:30 AM on July 6, 1945. Dr. Bradbury became the director of the Los Alamos National Laboratory in 1945 and served as head of the lab until 1970. *Jornada Del Muerto Valley, New Mexico. July 1945.*

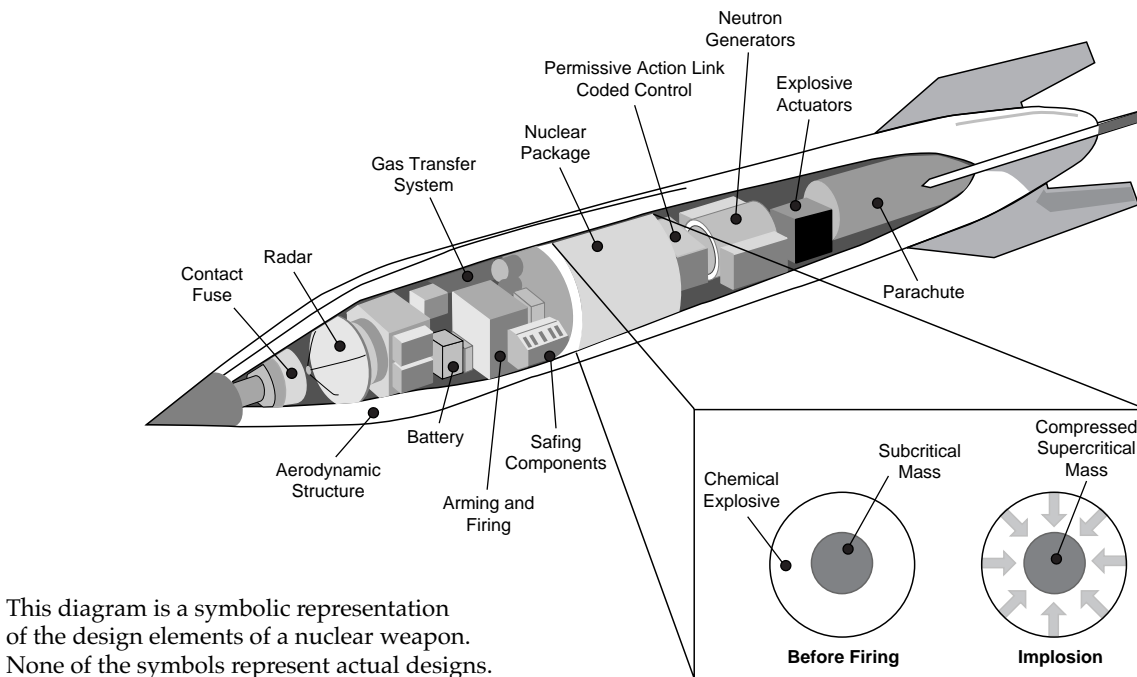
BACKGROUND

A nuclear weapon is a complex device consisting of many parts. A number of these parts require special materials in their manufacture; all of them have rigorous specifications for assembly. The essential ingredients of all nuclear weapons are fissile materials. Fissile materials are isotopes capable of being split or "fissioned" by a low energy neutron. Fission releases energy and additional neutrons and energy in the process leading to a self-sustaining chain reaction. Figure 2-1 illustrates the generic design elements of a nuclear weapon and explains the basic principles of its operation.

Most of the nuclear weapons complex was devoted to producing fissile and other nuclear materials. Nuclear materials production started with mined and milled uranium. Uranium was either enriched to high uranium-235 levels for direct use in nuclear weapons, or it was used to produce plutonium. In plutonium production, reactor fuel and targets made of uranium were irradiated in nuclear reactors then chemically processed to recover unused uranium and to extract plutonium. Tritium was produced in a similar fashion by separating lithium isotopes, then manufacturing lithium targets which were irradiated in reactors, then chemically processed to recover the tritium. Figure 2-2 illustrates a simplified flow of materials within the nuclear weapons complex.

The numerous activities that went into making nuclear materials and weapons and storing or disposing of the waste were conducted at hundreds of sites across the country. Some of the sites were owned by DOE and its predecessor agencies and operated by contractors; others were privately owned, but worked under contract with DOE; still others provided DOE and its operations contractors with needed services and supplies. Table 2-1 lists the major sites associated with the process categories and Figure 2-3 gives their locations.

Figure 2-1. Generic Design Elements of a Modern Nuclear Weapon



Nuclear explosions are produced by initiating and sustaining nuclear chain reactions in highly compressed material which can undergo both fission and fusion. Modern strategic, and most tactical, nuclear weapons use a nuclear package with two assemblies: the “primary,” which is used as the initial source of energy; and the “secondary,” which provides additional explosive power. The primary contains a central core, called the “pit,” typically composed of plutonium-239 and/or highly enriched uranium (HEU), and other materials. Plutonium-239 and HEU are fissile materials, capable of sustaining a chain reaction. HEU contains large fractions of uranium-235. The pit is surrounded by a layer of high explosive.

Primary Detonation

The primary nuclear explosion is initiated by detonating the layer of chemical high explosive that surrounds the “pit” which in turn drives the pit material into a compressed mass at the center of the primary assembly. Compression causes the fissile material to become supercritical. A neutron generator initiates a fission chain reaction in this supercritical mass. The implosion process is illustrated in the inset above.

Boosting

In order to achieve higher explosive yields from primaries with relatively small quantities of pit material, a technique called “boosting” is used. Boosting is accomplished by injecting a mixture of tritium (T) and deuterium (D) gas into the pit. The implosion of the pit along with the onset of the fissioning process heats the D-T mixture to the point that the D-T atoms undergo fusion. The fusion reaction produces large quantities of very high energy neutrons which flow through the compressed pit material and produce additional fission reactions.

Secondary Activation

Radiation from the explosion of the primary can be contained and used to transfer energy to compress and ignite a physically separate secondary component containing thermonuclear fuel. The secondary assembly may be composed of lithium deuteride, uranium, and other materials. As the secondary implodes, the lithium, in the isotopic form lithium-6, is converted to tritium by neutron interactions, and the tritium product in turn undergoes fusion with the deuterium to create a thermonuclear explosion.

Nonnuclear Components

Nonnuclear components include contact fuses, radar components, aerodynamic structures, arming and firing systems, deuterium and tritium gas transfer systems, permissive action link coded controls, neutron generators, explosive actuators, safing components, batteries, and parachutes.

Figure 2-2. How Nuclear Weapons are Made

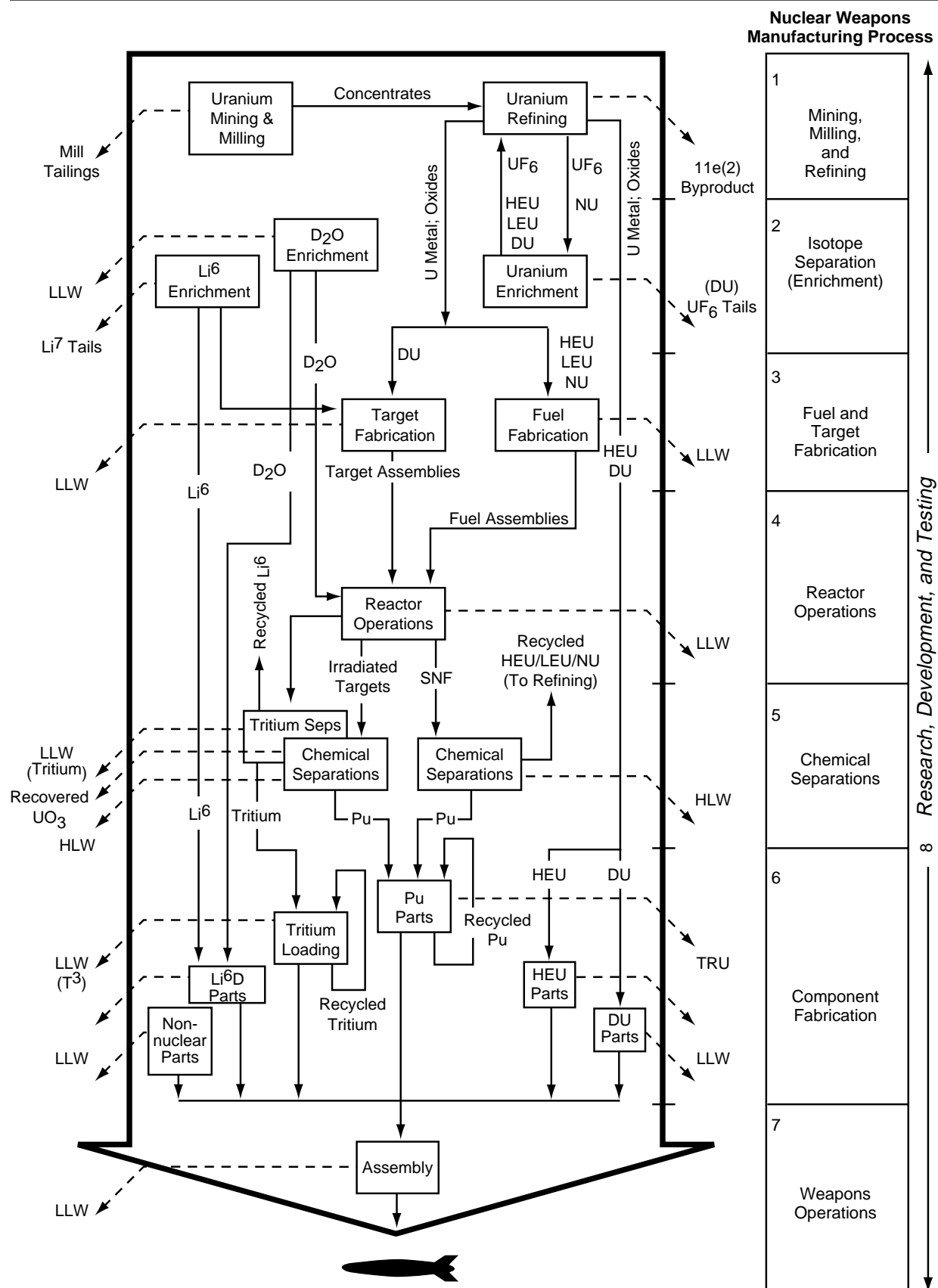


Table 2-1. Functional Processes at the Major Sites

STEP	PROCESS	MAJOR SITES
1	Uranium Mining, Milling, and Refining	<p><u>Mining & Milling</u>: Uranium Mill Tailing Remedial Action (UMTRA) Project mining and milling sites; other commercially-owned domestic mines; other commercially- and government-owned mills; foreign suppliers</p> <p><u>Ore Sampling</u>: Fernald and Middlesex</p> <p><u>Refining</u>: Fernald and Weldon Spring; (natural, depleted, and enriched uranium reactor fuel and targets); Oak Ridge Y-12 (weapon parts and highly enriched reactor fuel); Oak Ridge K-25, Paducah, and Portsmouth Gaseous Diffusion Plants (production of UF₆ feed)</p>
2	Isotope Separation	<p><u>Uranium</u>: Oak Ridge K-25; Paducah; and Portsmouth Gaseous Diffusion Plants</p> <p><u>Lithium</u>: Oak Ridge Y-12 COLEX and ELEX Plants</p> <p><u>Heavy Water</u>: Savannah River Site Heavy Water Plant; Dana Heavy Water Plant</p>
3	Fuel and Target Fabrication	<p><u>HEU</u>: Savannah River Site 300 M Area</p> <p><u>Other Uranium</u>: Fernald; Ashtabula; Hanford 300 Area; and Savannah River Site 300 M Area</p> <p><u>Enriched Lithium</u>: Oak Ridge Y-12 and Savannah River Site M Area</p>
4	Reactor Operations	<p><u>Hanford</u>: B, D, F, H, DR, C, KW, KE, and N Reactors</p> <p><u>Savannah River Site</u>: R, P, K, L, and C Reactors</p>
5	Chemical Separations	<p><u>Weapons Plutonium</u>: Hanford 200 East and West Areas (PUREX, REDOX, T and B Plants, 231-Z Plant); Savannah River Site (F Canyon complex)</p> <p><u>Uranium Recycling</u>: Hanford (PUREX, UO₃ Plant, REDOX, U Plant); Savannah River Site (H Canyon complex); Idaho National Engineering Laboratory (Idaho Chemical Processing Plant)</p> <p><u>Tritium</u>: Savannah River Site (Tritium Facility 230H Series)</p>
6	Weapons Component Fabrication	<p><u>Plutonium</u>: Rocky Flats; Hanford 234-5 Plutonium Finishing Plant; Los Alamos (TA-21 and TA-55)</p> <p><u>Highly Enriched and Depleted Uranium</u>: Oak Ridge Y-12; Rocky Flats</p> <p><u>Tritium (Including recovery and recycling)</u>: Mound; Savannah River Site (Tritium Facility)</p> <p><u>Lithium-6 Deuteride (Including recovery and recycling)</u>: Oak Ridge Y-12</p> <p><u>Plutonium Recycling</u>: Rocky Flats; Los Alamos (TA-55); Hanford Plutonium Finishing Plant</p>
7	Weapons Operations	<p><u>Other Nonnuclear</u>: Pantex; Oak Ridge Y-12; Mound; Kansas City; Pinellas</p> <p><u>Assembly and Dismantlement</u>: Sandia; Pantex; Burlington</p> <p><u>Modifications & Maintenance</u>: Pantex; Burlington; Sandia; Clarksville; Medina Modification Centers</p>
8	Research, Development, and Testing	<p><u>National Laboratories</u>: Los Alamos; Lawrence Livermore; Sandia (New Mexico and California)</p> <p><u>Test Sites</u>: Nevada Test Site; Bikini and Eniwetok Atolls; Christmas and Johnston Islands; Amchitka Island; Tonopah Test Range; Salton Sea Test Base</p>

Figure 2-3. Department of Energy Nuclear Weapons Sites





NUCLEAR WEAPONS PRODUCTION PROCESS AND HISTORY

Since the inception of the Manhattan Project in late 1942, the nuclear weapons complex has changed dramatically. The initial phase of its development, beginning during World War II and conducted by the U.S. Army Corps of Engineers Manhattan Engineer District (MED), involved the rapid construction of three sites: one for uranium enrichment (Oak Ridge, Tennessee); one for plutonium production (Hanford, Washington); and one for the research, design, and production of the first wartime atomic weapons (Los Alamos, New Mexico). A large number of private contractors supported these three sites by processing uranium ore into reactor fuel and enrichment feed stock.

After the war, authority over the nuclear weapons complex transferred to the recently-formed Atomic Energy Commission (AEC). Over the next decade, a major expansion coincided with a shift toward government-owned production facilities. Redundant facilities ensured that nuclear weapons production would not be interrupted by a problem at any single site. By the mid-1950s, all of the major weapons complex facilities had been established.

Budgetary considerations and an abundance of formerly scarce nuclear materials resulted in a shift from redundant sites to single-mission sites and a shutdown of some sites and materials production facilities in the mid-1960s. However, in the early 1980s, several of these weapons production facilities were modernized and restarted.

Significant Events: Uranium Mining, Milling, and Refining

- **During WWII**, the United States purchased the uranium content of high-assay uranium ore from the Belgian Congo (now Zaire), supplemented with ore and concentrate from Canada and the Colorado Plateau of the western U.S.
- Imported uranium ores and concentrates were stored at several locations in New York City, upstate New York, and Oak Ridge, Tennessee during **WWII**.
- **WWII** sampling and assaying was accomplished at several sites, including the Middlesex Sampling Plant in New Jersey.
- MED and early AEC uranium refining involved contractors in Tonawanda and Niagara Falls, New York; Cleveland, Ohio; Beverly, Massachusetts; St. Louis, Missouri; Deepwater and Bloomfield, New Jersey; Canonsburg, Pennsylvania; and Ames, Iowa.
- From **1946 until 1971**, AEC bought uranium ore and concentrate from Australia, Canada, Portugal, South Africa, and the Belgian Congo (later Zaire).
- In **1947**, K-25 began refining its own UF_6 feed. UF_6 feed plants were built at the Portsmouth and Paducah enrichment plants in the **early 1950s**.
- In **1948**, AEC instituted an incentive program to stimulate the domestic mining and milling of uranium. The amount of imported uranium was soon matched by domestic supplies. AEC's domestic uranium program was managed by the Grand Junction, Colorado office.
- Post-war refining was consolidated at the Mallinckrodt Chemical Works in St. Louis, Missouri and the government-owned Feed Materials Production Center (FMPC) in Fernald, Ohio, which opened in **1952**.
- In **1956**, the Weldon Spring plant near St. Louis, Missouri was converted from a conventional ordnance production facility and began refining operations. It assumed the functions of the downtown St. Louis uranium refining plant, which shut down in **1958**.
- Sampling was consolidated at Middlesex, New Jersey in the **mid-1940s** and moved to Fernald, Ohio and Weldon Spring, Missouri in the **mid-1950s**.
- The UF_6 production plants at K-25, Portsmouth, and Paducah closed in **1962**. After that time, commercial suppliers in Metropolis, Illinois converted uranium to UF_6 feed. UF_6 tails were also recycled into the enrichment plants as feed.
- The Fernald refinery was on standby from **1962** until the Weldon Spring, Missouri plant was closed in **1966**.
- U.S. government uranium ore purchases ended in **1962**, and uranium concentrate purchases halted in **1971**.
- The Fernald uranium refinery closed in **1972**, although processing of recycled uranium at FMPC continued until **1989**.



America's first uranium refinery. Here and in surrounding buildings, the Mallinckrodt Chemical Works converted raw uranium yellowcake into uranium oxide, green salt, and uranium hexafluoride. The Manhattan Project used uranium processed here as fuel for the world's first nuclear reactors and in the atomic bomb dropped on Hiroshima. After 15 years of operations, the downtown St. Louis uranium refinery closed in 1957. This uranium contaminated building was demolished in 1996. *St. Louis Sash and Door Works Building, St. Louis Downtown Site, St. Louis, Missouri. January 24, 1994.*

In the late 1980s and early 1990s, environmental and safety concerns and the end of the cold war caused many nuclear weapons production sites to shut down. However, a few key nuclear weapons production sites remain in operation at the present time.

The remainder of this chapter describes the eight weapons production process categories, identifies the major sites involved in each category, and briefly describes some of the major events in the history of U.S. nuclear weapons production.

Uranium Mining, Milling, and Refining¹

Mining and milling involve extracting uranium ore from the earth's crust and chemically processing it to prepare uranium concentrate (U_3O_8), sometimes called uranium octaoxide or "yellowcake." Uranium ores and concentrates are sampled and assayed to determine uranium content, as well as impurities and the existence of other constituents. About half of the uranium used in the U.S. nuclear weapons complex was imported from Canada, Africa, and other areas. The remainder came from the domestic uranium industry that grew rapidly in the 1950s. The first imported uranium, high-grade "pitchblende" ore containing up to 65 percent uranium oxide by weight, was milled in Canada and by domestic contractors. After World War II, imported uranium was purchased in the form of already-milled concentrates and high-grade ores. Domestic uranium was purchased as either ore or concentrate.

¹ Mining and refining of other materials used in nuclear weapons production, such as iron, aluminum, lead, beryllium, copper, nickel, mercury, lithium, boron, silver, and gold are not covered in this report. Their nuclear weapons program use represents only a small portion of total output.

Uranium concentrates were refined, or chemically converted, to purified forms suitable as feed materials for the next step in the process. Examples of these feed materials are uranium hexafluoride (UF_6) for enrichment at gaseous diffusion plants, and uranium tetrafluoride (UF_4), or metal, for fuel and target fabrication. Refining, as discussed in this report, also involves the recycling of various production scraps, production residues, and uranium recovered from fuel reprocessing.

Wartime uranium refining was performed by various contractors in several Eastern states. After the war, AEC built government-owned uranium refineries in Fernald, Ohio and Weldon Spring, Missouri.

Most domestic uranium mining and milling that occurred in open-pit or underground mines and at nearby mill sites resulted in very large volumes of slightly radioactive sand-like residues called mill tailings, which typically contain radioactive thorium, radium, radon, and nonradioactive heavy metals in low concentrations. The U.S. government also purchased a small amount of uranium concentrates from in situ solution mining, which produces no tailings. Uranium refining resulted in lesser amounts of tailings and other byproducts than were created through mining and milling. These byproducts are characterized chiefly by the presence of thorium, radium, and radon.

Isotope Separation (Enrichment)

Enrichment is the process of separating naturally occurring isotopes of the same element. The three elements that have been isotopically enriched in large quantities for use in the nuclear weapons complex are uranium, lithium, and hydrogen.²

Uranium Enrichment – Uranium enrichment began with natural uranium (NU) and resulted in enriched uranium (EU) and depleted uranium (DU). Uranium found in nature contains approximately 0.71 percent of the isotope uranium-235, the remainder being almost entirely uranium-238. EU is processed uranium containing more than a 0.71 percent concentration of uranium-235; DU, contains less than 0.71 percent uranium-235. Highly enriched uranium (HEU) contains 20 percent or more of uranium-235; it

Significant Events: Uranium Enrichment

- MED initially investigated four processes for the enrichment of uranium: gas centrifuge, thermal diffusion, electromagnetic spectrograph, and gaseous diffusion.
- The U.S. Navy built a pilot scale thermal diffusion plant at the Philadelphia Naval Yard in **1944**.
- During **WWII**, the S-50 thermal diffusion plant and the K-25 gaseous diffusion plant fed the Y-12 electromagnetic separation plant to produce the HEU for the Little Boy bomb. All of these plants were located in Oak Ridge, Tennessee.
- The S-50 and Y-12 enrichment plants shut down in **1945** and **1946**, respectively.
- K-25 was expanded between **1946** and **1954**, and gaseous diffusion plants were built at Paducah, Kentucky and Piketon, Ohio (the Portsmouth Plant) in the **early and mid-1950s**.
- The K-25, Portsmouth, and Paducah plants operated in series, with Paducah as the feed point, and its low enriched product split between K-25, which produced LEU and HEU, and Portsmouth, which produced HEU.
- The K-25, Portsmouth, and Paducah plants ceased producing HEU for weapons purposes in **1964**, dramatically decreasing their output, while production of LEU for production reactor fuel continued.
- K-25, Portsmouth, and Paducah increased their output in the **late 1960s** in response to growing demand for enriched uranium for the U.S. Naval Nuclear Propulsion Program and the nuclear power industry. Portsmouth produced the HEU for the Navy propulsion reactors.
- K-25 was shut down completely in **1987**.
- Under the Energy Policy Act of **1992**, the Portsmouth and Paducah plants were leased by DOE to the newly created United States Enrichment Corporation which continues to operate them.

² Boron isotope separation was also carried out, as were experiments with separating isotopes of plutonium and removing minor isotopes of uranium from irradiated uranium.

was fashioned into weapons components and also used as a reactor fuel, whereas low enriched uranium (LEU) and NU are used as reactor fuel for the production of plutonium. DU was used in weapon components and as targets for the production of plutonium-239. All of the uranium enriched during the Manhattan Project was HEU for weapons components. However, as early as 1950, LEU was used for reactor fuel.

The first U.S. uranium enrichment facilities were located in Oak Ridge, Tennessee. Additional enrichment plants were later built in Piketon, Ohio and Paducah, Kentucky.

Uranium enrichment has resulted in large amounts of DU in storage, large surplus facilities, uranium-contaminated scrap metal (from facility dismantlement), PCB-contaminated waste and uranium, technetium-99, and organic solvent contamination of soils and groundwater.

Lithium Enrichment – Lithium enriched in the lighter lithium-6 isotope was placed in production reactors to produce tritium and was also chemically compounded with deuterium to be used as a component in nuclear weapons. Natural lithium is about 7.5 percent lithium-6 and 92.5 percent lithium-7. Lithium was enriched at the Y-12 Plant in Oak Ridge, Tennessee using the column exchange (COLEX) and electric exchange (ELEX) processes. Both lithium enrichment processes used large amounts of mercury, and as a result, mercury is a major feature of the contaminated environmental media legacy at Y-12.

Heavy Water Production – Heavy water is used as a source of deuterium for weapons and as a moderator and coolant for nuclear reactors. Natural water contains small amounts of deuterium (0.015 percent), which was concentrated by a combination of hydrogen sulfide-water chemical exchange, water distillation, and electrolytic processes. Heavy water plants were located in Newport, Indiana and at the Savannah River Site in South Carolina.

Significant Events: Lithium Enrichment

- The Y-12 Plant in Oak Ridge, Tennessee was tasked with the development of lithium isotope separation technology in **1950**.
- Three processes were developed to the pilot plant stage: an organic exchange process (OREX), the ELEX process, and the COLEX process.
- Production-scale lithium enrichment using the ELEX process began at the Y-12 Plant in **1953**. Two large COLEX production plants were built in **1955**.
- The ELEX production plant was shut down in **1956**. One of the COLEX plants was shut down in **1959** and the other continued production until **1963**.
- The Li_6 stockpile is stored at the Y-12 and K-25 Plant. Lithium "tails" depleted in the Li_6 isotope are stored at the K-25 and Portsmouth plants, and a stockpile of unprocessed lithium feed is stored at K-25.

Significant Events: Heavy Water Production

- **During WWII**, small amounts of heavy water for research came from a variety of sources, including material captured in Germany, a small amount produced domestically by electrolysis and fractional distillation, and from a plant built for the Manhattan Project in Trail, British Columbia, Canada.
- The heavy water plants at the Savannah River Site, South Carolina and Newport, Indiana began operating in **1952** to supply large amounts of heavy water for the Savannah River Site reactors.
- The Dana heavy water plant in Newport, Indiana was shut down in **1957**.
- The Savannah River Site heavy water plant stopped deuterium production in **1982** after a staged shutdown. Re-enrichment of small amounts of degraded, recycled deuterium continues using a moderator rework unit at the Savannah River Site.

Fuel and Target Fabrication

Fuel and target fabrication consists of the foundry and machine shop operations required to convert uranium feed material, principally metal, into fuel and target elements used in nuclear materials production reactors. Some later production reactors used separate fuel and target elements, while early production reactors used the same elements for both fuel and targets. Uranium ingots were extruded, rolled, drawn, swaged, straightened, and outgassed to produce rods and plates. The rods were machined, ground, cleaned, coated, clad, and assembled into finished fuel.

Reactor fuel and target fabrication was initially carried out by private contractors and at the Hanford, Washington and the Savannah River, South Carolina production reactor sites. Within a decade, government-owned plants in Fernald, Ohio and Weldon Spring, Missouri took over part of this mission, supplying the fuel manufacturing plants at Hanford and the Savannah River Site.

Chemical conversion of uranium feed to metal and processing of uranium scrap and residue resulted in low-level waste and environmental contamination with uranium, acids, and solvents. Uranium metallurgy and machining also resulted in facilities becoming contaminated with uranium.

Significant Events: Fuel and Target Fabrication

- During the Manhattan Project, fuel for the Clinton X-10 reactor (later ORNL) and the Hanford B, D, and F production reactors was manufactured by companies in Detroit, Michigan; Columbus, Cleveland, Toledo, Warren, and Hamilton, Ohio; Fort Wayne, Indiana; Reading, New Kensington, and Springdale, Pennsylvania; Bridgeport, Connecticut; and Chicago, Illinois.
- By the **spring of 1945**, Hanford's 300 Area had assumed all of the fuel fabrication responsibilities for the site's reactors except extrusion. Hanford extruded uranium rods onsite from **1946 to 1948**, then shifted to rolled rods supplied by offsite private contractors. Hanford rolled uranium rods from **1950 to 1952**.
- Hanford manufactured lithium targets for tritium production from **1949 to 1952** and again from **1965 to 1967**. The site also made bismuth targets for polonium-210 production and lead-cadmium rods used as a neutron-absorbing "poison" to control reactors.
- The M Area at the Savannah River Site was built in **1952** to clad and assemble fuel elements for the five production reactors located there.
- Facilities at the Savannah River Site M Area manufactured lithium-aluminum targets for tritium production and targets for manufacturing americium, curium, plutonium-238, and other isotopes.
- Uranium slug machining for Hanford and the new Savannah River Site reactors was taken over by FMPC at Fernald, Ohio, which opened in **1952**, and the Weldon Spring plant in Missouri which opened in **1956**. Extrusion was performed by private contractors in Adrian, Michigan, and moved to Ashtabula, Ohio in **1961**. Fernald produced rolled uranium rods onsite.
- To meet the demands of supplying fuel for 13 operating production reactors, private contractors continued to support Fernald and Weldon Spring by machining uranium slugs in the **1950s**.
- In the **1950s**, production reactor fuel changed in several respects: natural uranium was replaced by LEU, solid cylinders were replaced by tubes, and, with the opening of the N Reactor at Hanford in **1963**, aluminum-clad fuel was supplemented by fuel clad with zirconium.
- By the time N Reactor started up at Hanford in **late 1963**, there were sufficient stocks of LEU at Fernald to supply the reactor without requiring additional LEU from the gaseous diffusion plants.
- Weldon Spring shut down in **1966**, and Fernald subsequently assumed all of the fuel fabrication mission.
- In **1968**, the Savannah River Site converted to HEU fuel and DU targets. The HEU was supplied by recycling research, Naval and production reactor spent fuel and recovering the HEU at the Savannah River Site H Canyon and INEL ICPP. Weapons-grade HEU stored at Y-12 was also used to supply some fuel for Savannah River Site reactors. Fernald continued to supply LEU slugs for the N Reactor and the DU targets for the Savannah River Site reactors.
- Hanford's 300 Area made only N Reactor fuel after **1971**. The facilities shut down in **1972** and later resumed production of N Reactor fuel in **1981**.
- Fuel and target fabrication at Hanford's 300 Area ceased permanently in **1987** with the closure of N Reactor. Production at the Savannah River Site M Area and Fernald ended in **1989** with the shutdown of the last Savannah River Site reactor.

Reactor Operations

Reactor operations include fuel and target loading and removal, reactor maintenance, and the operation of the reactor itself. Experimental reactors were built by MED in the Chicago area, Oak Ridge, and Hanford. Nine full-scale production reactors were located at Hanford, Washington, and five others were built at the Savannah River Site in South Carolina.

Almost all of the radioactivity in the environmental legacy of nuclear weapons production was created by reactor operations. Irradiated fuel and targets are highly radioactive. The components of the reactor cores also became highly radioactive over time. However, the waste volume attributed to this activity is primarily composed of low-level waste from reactor support operations. The highly radioactive spent fuel and target materials typically went on to chemical separations, but an inventory of unprocessed spent fuel and targets remain in storage. Cooling the reactors contaminated several large bodies of water including the Columbia River at the Hanford Site and PAR Pond at the Savannah River Site. The reactors also required a large number of support facilities that are now surplus.

Significant Events: Reactor Operations

- Five prototype, test, and research reactors operated in the U.S. during **WWII**—one at the University of Chicago, two in the Palos Forest Preserve outside Chicago, one in Oak Ridge, and one at Hanford. Three full-scale production reactors (B, D, and F) were operating at Hanford by **mid-1945**.
- To limit radiation damage to the reactor's core, the B Reactor at Hanford was shut down in **1946** and restarted in **1948**.
- Between **1948** and **1955**, Hanford built five more production reactors (H, DR, C, KW, and KE). During their life cycles, the original eight Hanford reactors (including B, D, and F), produced weapons-grade plutonium and small quantities of other isotopes (e.g., polonium-210 and tritium).
- AEC established the Savannah River Site near Aiken, South Carolina, in **1951**. Five production reactors (R, P, L, K, and C) at the Savannah River Site manufactured tritium, weapons-grade plutonium, and other isotopes (including uranium-233, neptunium, plutonium-238 and -242, americium, and curium).
- A ninth Hanford reactor, N Reactor, began operating in **late 1963** to make weapons-grade plutonium, fuel-grade plutonium for the experimental breeder reactor program, and steam to generate electric power. N Reactor also made uranium-233 and small amounts of tritium.
- R Reactor at the Savannah River Site was shut down in **1964**.
- All of the original eight Hanford reactors were shut down between **1964** and **1971** as a result of the decreased need for weapons-grade plutonium.
- L Reactor at the Savannah River Site was shut down in **1968** when the Savannah River Site reactors were converted to use HEU fuel and DU targets.
- Beginning in **1981**, DOE began to blend excess fuel-grade plutonium from N Reactor with super-grade plutonium from Savannah River Site to produce weapons-grade plutonium.
- L Reactor at the Savannah River Site was restarted in **1985**.
- N Reactor at Hanford was shut down permanently in **1987**.
- By **1990**, all available N-Reactor-produced fuel-grade plutonium had been blended.
- P, L, K, and C reactors continued to operate at the Savannah River Site until late **1988**.

Significant Events: Chemical Separation

- The bismuth phosphate process for extracting plutonium from irradiated uranium was demonstrated in a pilot plant alongside the Oak Ridge X-10 Reactor in **1944**.
- The T Plant in the Hanford 200 West Area and B Plant in the Hanford 200 East Area opened in **1944** and **1945**, respectively. The plants separated plutonium from spent fuel using the bismuth phosphate process. The B and T Plants at Hanford shut down in **1952** and **1956**, respectively. Together the two plants processed 7,000 metric tons of spent fuel.
- The REDOX process was developed at Hanford in the late 1940s and used in the site's REDOX plant (also known as the S Plant) from **1951** through **1967**. The REDOX Plant at Hanford operated until **June 1967**, processing over 19,000 metric tons of spent fuel during its lifetime.
- The PUREX process was demonstrated at Knolls Atomic Power Laboratory in Schenectady, New York, and used at F and H Canyons at the Savannah River Site and the PUREX Plant at Hanford. The F Canyon began operation in **November 1954**. H Canyon started up in **July 1955**, and Hanford's PUREX Plant started up in the Hanford 200 East Area in **January 1956**.
- The Idaho Chemical Processing Plant (ICPP) at the Idaho National Engineering Laboratory began using variants of PUREX to process spent Navy and experimental reactor fuel for recovery and recycling of the HEU in **1953**. A new "head end" dissolving facility using the fluorine dissolution process, was built at ICPP in the **mid-1980s**.
- The ICPP shut down in **1992**. During its operation, it recovered a total of 31.5 metric tons of uranium from spent Naval (5.1 metric tons), research, and test reactor fuel.
- The U Plant at Hanford, originally built during WWII to separate plutonium but used instead as a training facility, was modified and used to recover enriched uranium from the site's high-level waste storage tanks from **1952** until **1958**. U Plant employed a process similar to PUREX.
- The PUREX Plant at Hanford was placed on standby in **1972** because of an excess of separated fuel-grade plutonium.
- After the Savannah River Site reactors began using HEU fuel and DU targets in **1968**, the F Canyon was given the mission of processing the irradiated DU targets and producing plutonium-239 as well as americium, curium, and other isotopes; H Canyon was assigned to process the HEU spent fuel and to recover uranium-235, neptunium-237, and plutonium-238.
- At Savannah River Site, plutonium-238 recovery operations shifted to the new HB Line in **1985**.
- The PUREX Plant at Hanford was restarted in **1983**. After restart, a new line at PUREX was used to convert plutonium nitrate solutions to more stable plutonium oxide. The plutonium oxide was transferred to the Plutonium Finishing Plant (PFP) in the Hanford 200 West Area for conversion to metal.
- Hanford's PUREX Plant operated intermittently in the late **1980s** and closed permanently after a short cleanout run in **1990**.
- The first Savannah River Site tritium facility was built in F Area in **1955** to recover tritium from irradiated lithium-6 targets. A new, larger facility in H Area replaced it in **1958**, and the current Savannah River Site tritium facility began operating in **1993**.
- Since **1968**, the Hanford B Plant has been used to remove, encapsulate, and store radioactive cesium and strontium from the Hanford high-level waste tanks.
- In **1953**, the original bulk reduction building of U Plant, 224U Building, was modified and started operating as the UO₃ Plant. The UO₃ Plant solidified recovered uranium from U Plant, REDOX, and PUREX. The plant shut down from **1972** until **1984**, shut down again in **1990**, and operated for a brief period of time in **1994**.
- At the Savannah River Site during the **1980s**, the FA Line solidified recovered DU. HB Line prepared neptunium-237 and plutonium-238 and FB Line produced plutonium-239.
- The FB Line at the Savannah River Site shut down in **December 1989** for maintenance, and the F Canyon shut down in **September 1991** as a result of safety concerns. H Canyon also shut down in **1991** in response to the Secretary of Energy's determination to discontinue spent fuel reprocessing.
- F Canyon restarted in **1996** to stabilize nuclear materials.
- The PFP (234-5 Z Building) at Hanford converted plutonium nitrate into more stable plutonium oxide and metal from **1950** until **1980**, and again from **1984** until **1990**.
- Due to a **1985** accident at the PFP, plutonium oxide from Hanford was sent to LANL TA-55 for conversion to metal for several months.

Chemical Separations

Chemical separation is the process of dissolving spent nuclear fuel and targets and isolating and concentrating the plutonium, uranium, and other nuclear materials they contain. This category also includes the reprocessing of spent nuclear fuel to recover, purify, and recycle uranium for reuse in the nuclear weapons programs and the recovery of uranium from high-level waste at Hanford. Three basic chemical separation processes were used on a production scale in the United States: bismuth phosphate, reduction oxidation (REDOX), and plutonium uranium extraction (PUREX). Chemical separation plants were located at Hanford, Washington; the Savannah River Site, South Carolina; and the Idaho National Engineering Laboratory.

Chemical separation of spent fuel and target elements produced large volumes of highly radioactive, high-level waste, and large quantities of low-level radioactive wastewater, solid low-level waste, and mixed low-level waste. Processing of plutonium and other transuranic isotopes also results in transuranic waste. Waste generation per unit of dissolved heavy metal decreased by a factor of approximately 100 between 1945 and 1960. Very large volumes of water from chemical separation plants³—containing low levels of radionuclides and hazardous chemicals—were discharged to the ground, resulting in soil and groundwater contamination.



Hanford workers sit down to dinner at one of eight mess halls at the Hanford Construction Camp, built on the former site of the town founded between 1905 and 1910 by Judge Cornelius Hanford. The construction camp housed 50,000 people at its peak in 1944, and included two movie theaters, a post office, a bank, and a bowling alley. *Hanford Construction Camp, Washington. 1944.*

³ The Department has estimated that the Hanford 200 Areas, where the site's chemical separation plants are located, discharged nearly 350 billion gallons of wastewater to the ground between 1945 and 1991.

Significant Events: Component Fabrication

- Most of the components for the **WWII** Manhattan Project bombs were made at Los Alamos, New Mexico. Some parts were made offsite by ordnance plants, machine shops, and other suppliers.
- Hanford took over the manufacture of plutonium pits at the Plutonium Finishing Plant in **1949**.
- The Y-12 Plant in Oak Ridge, Tennessee began making uranium weapon parts in **1948** and lithium deuteride weapon parts in the **mid-1950s**.
- Although it was no longer the lead site for nuclear component fabrication after **1949**, Los Alamos National Laboratory was a backup production facility and designed, developed, and fabricated these components for test devices. The original plutonium production area built at Los Alamos in late **1945**, DP Site (also known as TA-21), was replaced by TA-55 in **1978**.
- High explosive main charges were produced at the Salt Wells Pilot Plant at China Lake Naval Ordnance Station in California from the fall of **1946** through **1954**.
- The Mound Laboratory in Miamisburg, Ohio was built to manufacture polonium-beryllium initiators and other weapon parts in **1946**.
- The Burlington Army Ordnance Plant in Iowa, primarily a weapons assembly facility, also made high explosive main charges from **1947** until **1975**.
- The Pantex Plant near Amarillo, Texas, was converted from a WWII conventional munitions plant in **1951** to serve primarily as a weapons assembly plant, although Pantex also manufactured high explosive weapons components.
- The Kansas City Plant in Missouri began making nonnuclear weapon parts (electronics, rubber, plastic foams, adhesives, outer casings, and others) in **1949**.
- Steel component fabrication functions were moved from various sites across the nation to the South Albuquerque Works in New Mexico in **1952**.
- Also in **1952**, the Rocky Flats Plant near Golden, Colorado began manufacturing plutonium, HEU, and DU pit parts. Rocky Flats assembled parts from Hanford, Y-12, and the South Albuquerque Works into completed pits.
- The Savannah River Site began loading tritium into weapon components in **1955**.
- The Pinellas Plant was built in Largo, Florida, in **1957** to produce precisely timed neutron generators to initiate chain reactions in nuclear weapons.
- Mound was assigned new production functions beginning in **1955**, including detonators, cable assemblies, and firing sets and stopped producing initiators after the Pinellas Plant began producing accelerator-type neutron generators in **1957**.
- Rocky Flats ceased making HEU components in **1962**, leaving Y-12 Plant as the sole site for these components.
- AEC eliminated Hanford's plutonium component manufacturing mission in **1965**, leaving Rocky Flats the sole source of plutonium components.
- Production of beryllium components became part of normal operations at Rocky Flats in **1958**.
- The South Albuquerque Works closed in **1966**, transferring its stainless steel pit component and tritium reservoir fabrication missions to Rocky Flats.
- Mound began tritium work in **1954** and, in **1969**, began retrieving tritium from retired weapons to be recycled and sent to Savannah River Site for purification and reuse.
- Plutonium scrap and residue recycling operations were performed at the Hanford PFP, Rocky Flats, the Savannah River Site, and Los Alamos National Laboratory.
- From **1968** to **1990**, Y-12 received recovered high-enriched UO_3 from ICPP and uranium nitrate from Savannah River Site H Area and reduced it to HEU metal, which was either stockpiled or used as fuel in the Savannah River Site production reactors.
- Due to the end of the Cold War, the DOE mission to fabricate weapons components was terminated. Rocky Flats production activities ended in late **1989**, and Mound and Pinellas ended their production activities in **1995**. Y-12 now receives and stores nuclear weapon components and processes and stores HEU and lithium-6.

Component Fabrication

Weapons component fabrication includes the manufacturing, assembly, inspection, bench testing, and verification of specialized nuclear and nonnuclear parts and major subassemblies. Also included in this category is chemical processing to recover, purify, and recycle plutonium, uranium, tritium, and lithium from retired warheads, and from component production scrap and residues, as well as the maintenance, recharging, dismantlement, and materials recovery conducted separately on individual components.

The major nuclear component fabrication sites were Los Alamos National Laboratory in New Mexico; the Rocky Flats Plant, near Boulder, Colorado; the Y-12 Plant in Oak Ridge, Tennessee; and the Plutonium Finishing Plant in Hanford, Washington. Nonnuclear components were manufactured chiefly at the Mound Plant in Miamisburg, Ohio; the Kansas City Plant in Missouri, the Pinellas Plant in Largo, Florida; and the Pantex Plant near Amarillo, Texas.

Like many conventional manufacturing processes, nonnuclear component fabrication activities have resulted in hazardous waste and contamination of environmental media and facilities by solvents and heavy metals. High-explosive manufacturing has resulted in facilities and environmental media contaminated with explosives. Fabrication of nuclear components led to the presence of nuclear materials (especially plutonium) in waste, contaminated environmental media and surplus facilities, and created stockpiles of nuclear materials, much of which are no longer needed for the nuclear weapons program.

Weapon Operations

Weapon operations includes the assembly, maintenance, and dismantlement of nuclear weapons. Assembly is the final process of joining together separately-manufactured components and major parts into complete, functional, and certified nuclear weapon warheads for delivery to the Department of Defense (DoD). Maintenance includes the modification and upkeep of a nuclear weapon during its life cycle.⁴ Dismantlement involves the reduction of retired warheads to a nonfunctional state and the disposition of their component parts. The dismantlement process yields parts containing special nuclear materials, high explosives, hazardous materials, and other components with hazardous and nonhazardous properties. Some parts are returned to the facility where they were originally produced. Other parts either are maintained in storage (e.g., plutonium pits) or are dispositioned onsite. Disposition processes include

Significant Events: Nuclear Weapons Operations

- In **July 1945**, MED acquired part of Oxnard Field (now Kirtland Air Force Base) in Albuquerque, New Mexico and converted it into a weapons assembly site (Sandia Base).
- Technical Area 2 at Sandia Base assembled nuclear weapons until **1957**.
- The Iowa Army Ordnance Plant in Burlington was converted to a weapons assembly plant in **1947**. Assembly functions performed at Sandia Base were transferred to the Burlington assembly plant by **1949**.
- The Pantex Plant, near Amarillo, Texas was converted to a nuclear weapons assembly plant in **1951**.
- Both the Burlington and Pantex Plants performed assembly activities between **1951** and **1975**, when Burlington functions were transferred to Pantex.
- Until **1962**, AEC stored fissile cores and initiators in separate facilities on military nuclear weapons stockpile storage sites. Maintenance and modification were also done at the bases.
- Two supporting plants were constructed in **1958**, the Clarksville Modification Center on the Fort Campbell Military Reservation in Clarksville, Tennessee and the Medina Modification Center in Medina, Texas. These sites performed tasks such as weapon repair and modification and component modification and testing. Clarksville closed in **1965** and Medina closed in **1966**.
- Final assembly of test devices has been performed at the Nevada Test Site since it opened in **1951** and at the Pacific and other test sites.

⁴ Field replacement of limited-life components by the military is not included in this category.

crushing, shredding, burning of main high-explosive charges, and firing of small energetic components. DOE is the steward of the weapon until all components have been stabilized, stored, and disposed.

Weapon operations were chiefly done at the Pantex Plant near Amarillo, Texas; the Iowa Army Ordnance Plant in Burlington, Iowa; Technical Area 2 of Sandia National Laboratory; and the Clarksville, Tennessee and Medina, Texas modification centers.

The environmental legacy resulting from assembly and maintenance is relatively small compared to the legacy resulting from the other weapons production steps. This is partly because all the radioactive materials handled in this process are generally in the form of sealed weapons components.

Research, Development, and Testing (RD&T)

Weapons research and development were conducted at MED, AEC, and DOE weapon laboratories and test areas and as a small part of the mission of other laboratories (DoD laboratories are not included in this analysis). As used in this report, nuclear weapons RD&T includes the design, development, and testing of nuclear weapons and their effects. Localized RD&T to support specific site missions (such as fuel fabrication) is generally considered in this report to be part of each site's mission.

The main U.S. nuclear weapons research and development facilities are the Los Alamos, Lawrence Livermore, and Sandia National Laboratories.

Nuclear weapons research and development activities have produced a broad assortment of waste and large volumes of contaminated soil and debris.

Testing – The United States has conducted a total of 1,054 nuclear tests, including 24 joint U.S.-United Kingdom tests. These tests have been conducted for several purposes: 891 detonations were primarily to prove that a weapon or device would function as designed, to advance weapon design, or to verify the reliability of weapons in the stockpile; 100 detonations were chiefly to explore the effects of nuclear weapons; 88 were safety experiments and 4 were storage- and transportation-related experiments; 24 were joint U.S.-United Kingdom detonations; 7 detonations were to develop means of detecting nuclear explosions from a great distance; and 35 detonations explored nonmilitary uses of nuclear explosives. (Some tests comprised multiple detonations.)

Significant Events: Nuclear Weapons Research and Development

- Much of the early theoretical and experimental work leading to development of nuclear weapons was conducted in Europe in the first four decades of the twentieth century.
- American universities made several important contributions to the development of nuclear physics in the **1930s**.
- By **mid-1942**, government support resulted in research becoming concentrated at Columbia University in New York, the University of California in Berkeley, and the University of Chicago Metallurgical Laboratory.
- The U.S. Army Corps of Engineers began construction at Los Alamos in **1942**. Scientists assembled from many research laboratories and universities were tasked with research, design, and engineering of the first nuclear weapons. Many other research institutions and universities also contributed to the development of the atomic bomb.
- On **November 1, 1949**, Sandia Laboratory was formed from the Sandia branch of Los Alamos on the grounds of Oxnard Field (now Kirtland Air Force Base) near Albuquerque, New Mexico. The mission of the new laboratory was the design of nonnuclear components of weapons.
- AEC established the University of California Radiation Laboratory in Livermore, California as a second nuclear design laboratory in **1952**. The facility is now known as the Lawrence Livermore National Laboratory.
- In **1956**, a branch of Sandia National Laboratory was established at Livermore, California.
- Most of the DOE National Laboratories, including Oak Ridge, Brookhaven, Argonne, and Idaho, have performed basic research that has contributed to nuclear weapons development.

U.S. nuclear weapon testing has been carried out principally in the South Pacific and at the Nevada Test Site near Las Vegas, Nevada. However, several tests have been performed at other locations.

Testing has resulted in large areas of contaminated soil and other environmental media, some highly contaminated. Some safety experiments have resulted in significant quantities of plutonium dispersed on the surface. Underground explosions have left underground cavities filled with a vitrified mixture of soil and explosion residues. Surface subsidences have resulted from the collapse of the underground cavities.

U.S., Soviet, British, French, and Chinese atmospheric nuclear weapons tests have collectively increased the current average annual effective radioactive dose equivalent to the population by a fraction of one percent.

Significant Events: Nuclear Weapons Testing

- During **1944** and **1945**, nonnuclear testing for the Manhattan Project was done at four sites: the Salton Sea Test Base, Muroc Air Base and China Lake Naval Ordnance Testing Station in California, and Wendover Field in Utah.
- The first U.S. nuclear weapons test, code-named "Trinity," was near Alamogordo, New Mexico, on **July 16, 1945**.
- Bikini Atoll in the South Pacific was the initial site of MED and AEC weapons testing following the end of World War II. Between **1946** and **1958**, 23 tests took place at Bikini.
- Enewetak Atoll in the South Pacific was used for 43 atmospheric nuclear tests between **1948** and **1958**, including the first thermonuclear test in **1952**.
- Atmospheric nuclear weapon tests have also been carried out in the upper atmosphere or at sea in the Johnston and Christmas Island areas (12 and 24 tests, respectively, at the 2 sites between **1958** and **1962**), the Pacific Ocean (4), and at high altitude over the South Atlantic Ocean (4).
- The Nevada Test Site was established in **1951** and was originally known as the Nevada Proving Grounds. There have been 928 nuclear tests at The Nevada Test Site since it was opened, including 100 atmospheric tests.
- At the Nevada Test Site, test shots Pascal A & B and Rainier were the first attempts to gather data for underground containment, and prepared the way for confining all tests underground in accordance with the Limited Test Ban Treaty.
- Since **1963**, all U.S. nuclear tests have been conducted underground.
- A number of transportation experiments involving the detonation of high-explosive charges without producing a nuclear yield were carried out on the Nellis Air Force Range adjacent to the Nevada Test Site in **1957** and **1963**.
- Weapons-related nuclear Test Faultless was detonated in central Nevada in early **1968**.
- Two megaton-range weapons-related tests were conducted on Amchitka Island, Alaska, in **1969** and **1971**.
- Underground nuclear explosions for the "Vela Uniform" project to improve the capability to detect, identify, and locate underground nuclear explosions were carried out in Fallon, Nevada; Hattiesburg, Mississippi; Amchitka, Alaska; and the Nevada Test Site between **1963** and **1971**.
- Between **1961** and **1973**, 35 nuclear devices were detonated at a number of continental sites (including the Nevada Test Site) as part of the "Plowshare" program to investigate the use of nuclear explosives in excavation and natural gas and oil production. These tests are not considered to be part of the nuclear weapons development legacy.
- Salton Sea Test Base in California was used in the **1940s** and **1950s** as a sea level ballistics range to obtain performance data on inert nuclear weapons prototypes. Salton Sea activities were transferred to the Tonopah Test Range in **1961**.
- The Tonopah Test Range in Nye County, Nevada, was established in **1957** for the testing of nonnuclear systems and components of bombs. Typical tests conducted at this site include bomb delivery systems, bomb delivery retardation chutes, and artillery shell trajectories.
- Restoration for Bikini Atoll was performed in **1969** by a joint AEC/DoD/Department of Interior effort organized around a Naval Sea Task Group.
- The Enewetak Proving Ground was placed on standby after Operation Hardtack I in **1958** and officially abandoned in **1960**. It was remediated by a joint DOE/DoD/Department of Interior effort, with the actual cleanup performed by the Army Corps of Engineers between **1978** and **1980** and managed by the Defense Nuclear Agency.

